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STRATIGRAPHY OF THE PLIO-PLEISTOCENE STRATA IN THE TWELVEMILE CREEK AREA, SAN FRANCISCO PENINSULA, CALIFORNIA

By

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Abstract: Rocks in the Twelvemile Creek area are mostly sedimentary, belonging to the Franciscan, Merced, and Colma formations. The Merced Formation consists of about 1000 meters of richly fossiliferous marine strata, which correlate with the upper marine part of the type section of the Merced, and are entirely of upper Pliocene age. The nonmarine Colma Formation is subdivided into a lower massive sand unit a few hundred meters thick, and a thin clay-rich upper unit, and these units are suggested to have been deposited respectively, during a high stand and a low stand of sea level during the Pleistocene. The Merced and Colma formations in this area are separated by a high-angle fault, which is a northward continuation of the Serra Fault. The Serra Fault in this area nearly parallels the San Andreas Fault, gradually diverging from it towards the north.

The Merced Formation in the Twelvemile Creek area is abundantly fossiliferous and contains a known fauna of over 50 species. The echinoids (*Scutellaster*), nassariid gastropods (*Nassarius*), and turrid gastropods (*Ophiodermella*) are the most useful fossils for correlation of Merced Formation strata. Species of the gastropod *Ophiodermella* have restricted stratigraphic ranges in the Merced Formation and probably can be used for regional correlations of Plio-Pleistocene strata. The species *Ophiodermella graciosana* (Arnold, 1907), *O. mercedensis* (Martin, 1914), and *O. incisa* (Carpenter, 1864) occur in stratigraphic succession, and differ in having progressively weaker ornament and increasing spire height from *O. graciosana* to *O. incisa*.

Introduction

The Twelvemile Creek area lies along the topographic crest of the San Francisco Peninsula and is characterized by high topographic relief with deep valleys incised into soft and semiconsolidated rock units, which have been uplifted along faults running in a NW–SE direction. The most important fault is the predominantly strike-slip San Andreas Fault, which has been intermittently active over a long period of geologic time and has had a controlling influence on deposition of late Cenozoic sediments in this area. The fault is believed to have controlled the formation of the depositional basin, its size and form, and to have influenced the types of sediments deposited within it.

The San Francisco Peninsula basin is one of several Pliocene or Plio-Pleistocene basins that formed along the northern California coastline during the time preceding the formation of San Francisco Bay. In early Pliocene times, subsidence along the San Andreas Fault created the depositional basin which now contains the Merced Formation on the San Francisco Peninsula. A thin layer of nonmarine sediments was deposited unconformably over bedrock of Fran-

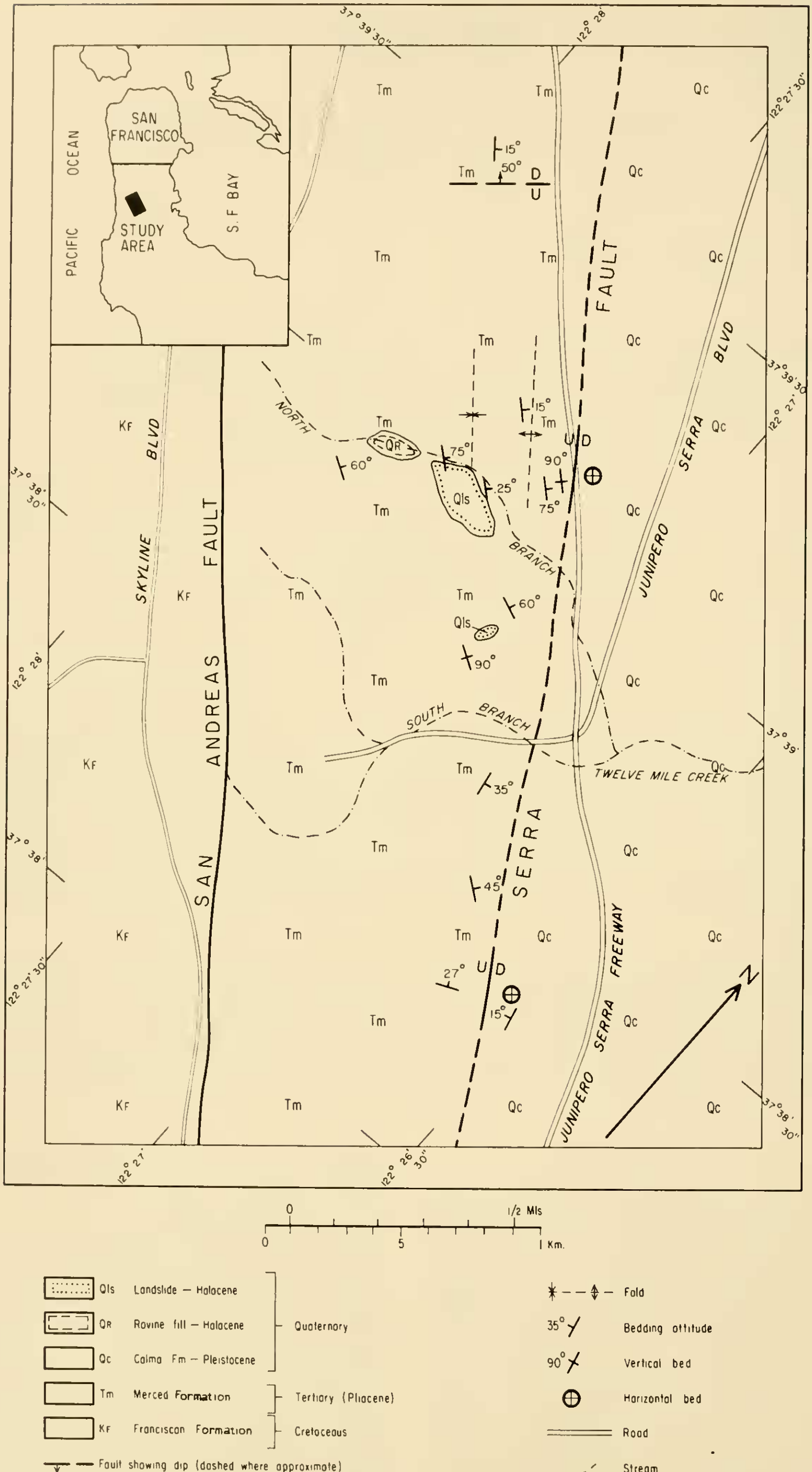


FIGURE 1. Geologic map of the Twelvemile Creek area, San Mateo County, San Francisco, California.

ciscan Formation greenstones, followed conformably by a change to marine deposition, with marine deposits accumulating continuously until the early Pleistocene when deposition became dominantly nonmarine and intermittent. Throughout this period, deposition took place in shallow-water conditions, and most deposition was very close to sea level.

The late Cenozoic marine and nonmarine sedimentary rocks in this basin, named the Merced Formation by Lawson (1893), are exposed in a long NW–SE trend parallel to the San Andreas Fault. The type exposures of the formation along the ocean cliffs to the northwest have been studied by Glen (1959) and Hall (1965a, 1965b), but there has never been any detailed work on the strata in the Twelvemile Creek area. The latter exposures provide the only stratigraphic section of the Merced Formation on the San Francisco Peninsula other than the type exposures along the ocean cliffs.

As part of a study of the strata within this basin, a geologic map was prepared of the area around the head of Twelvemile Creek on the San Francisco Peninsula (Fig. 1). This area includes the San Andreas Rift Zone and the young sediments northeast of the fault, encompassing an area between Skyline Boulevard on the west and Junipero Serra Boulevard on the east. The map is solely the work of the author except for some details of the trace of the San Andreas Fault taken from the geologic map of the San Francisco South quadrangle by Bonilla (1965, 1971).

This investigation began in the winter months of 1969 and continued through 1970, during a period of time when excavations combined with winter rains created favorable exposures over large areas within the Serramonte and Westborough development districts in the towns of South San Francisco, San Bruno, and Pacifica. I am indebeted to Warren O. Addicott of the U.S. Geological Survey for encouragement and help in preparing the manuscript, and I thank him and the U.S. Geological Survey for photographs of the fossils illustrated here. Also, colleagues Maurice E. Kaasa and John Marr expressed much interest and accompanied me in the field.

Fossil locality descriptions are recorded in the Museum of Paleontology, University of California, Berkeley. Illustrated fossils are stored in the U.S. National Museum and have received type numbers from their catalogs.

Major Geologic Structures

Two major faults, the San Andreas Fault and the Serra Fault, control the structural trends in the Twelvemile Creek area. Both faults are oriented NW–SE, and the Serra Fault is probably generated from the San Andreas Fault, although both appear to be high-angle faults with significant vertical displacement. These faults cut the map area into three distinct structural blocks, each containing the exposures of a different sedimentary formation. The structural block west of the San Andreas Fault contains metasediments and greenstones of the Franciscan Formation. The central block, between the San Andreas and Serra faults, contains exposures of the Merced Formation which have been uplifted and tilted so that they now have a strike NW–SE, parallel to the San Andreas Fault, and dip steeply towards the north and east. The structural block east of the Serra Fault contains exposures of the Colma Formation which have not been significantly deformed and are essentially flat-lying and unconsolidated.

San Andreas Fault

The segment of the San Andreas Fault within the map area occurs as a well-defined rift zone of intensely sheared rocks a few tens of meters wide. Before construction work obliterated most of the topographic expression, the rift zone was identifiable by a series of sag ponds in the area. Exposures made during the course of construction work showed that the actual limits of the rift correspond closely to the mapped limits as determined by topographic expression.

The fault is tectonically active in this area (Bonilla 1959). The most recent significant activity on the fault occurred during the 1957 San Francisco earthquake, although small earth tremors which are associated with the San Andreas Fault system are a frequent occurrence. The last significant disruption of the ground surface along the fault occurred during the 1906 San Francisco earthquake when lateral displacement of a couple of meters developed along the fault (Lawson and others 1908; Bonilla 1959).

Serra Fault

The Serra Fault was named by Bonilla (1965) from surface exposures of a high-angle fault located about one kilometer south of the Twelvemile Creek area. Within the map area this is a high-angle fault tending NW–SE approximately parallel to the San Andreas Fault. It separates steeply dipping Merced Formation sediments from undeformed flat-lying Colma Formation sediments. Bonilla (1965) mapped the fault in the type area as a reverse fault with rocks of the Franciscan Formation thrust over rocks of the Merced and Colma formations. In the Twelvemile Creek area the fault is clearly high-angle, but not demonstrably reverse or normal in orientation. It has a nearly linear trend, diverging gradually from the San Andreas Fault toward the north, and is in line with the segment of the fault mapped by Bonilla (1965). It has been mapped for a distance of over four kilometers.

The Serra Fault lies close to the trend of the "Foothills Thrust" fault, a postulated north-south high-angle thrust fault lying east of the San Andreas Fault (Willis 1938). Bonilla (1959) discusses this proposed fault, but does not use the name within the San Francisco South quadrangle. The Serra Fault appears to be a secondary fault of the type proposed by Willis (1938), an upthrust fault connected to the San Andreas Fault at depth, bounding a wedge-shaped structural block. Upward movement of the block from lateral compression could create thrusted fault boundaries. The upthrown side of the Serra Fault in the map area matches with the upthrust movement on the segment to the south, and suggests that the fault is an upthrust throughout its mapped length.

Folds

There is one conspicuous NW–SE tending fold within the Twelvemile Creek area. This is developed in strata of the Merced Formation adjacent to the Serra Fault north of the north branch of Twelvemile Creek. It is a structural terrace consisting of a narrow band of strata with low dips, within a sequence of more steeply dipping strata.

Stratigraphy

Three major stratigraphic units are present within the Twlevemile Creek area. The oldest is the Franciscan Formation, a mixed unit of greenstones and metasediments, of Jurassic–Cretaceous age. The next younger unit is the Merced Formation, a richly fossiliferous marine unit of Pliocene and Pleistocene age which was deposited on an eroded surface of the Franciscan Formation. The youngest unit is the Colma Formation, a flat-lying nonmarine unit of Pleistocene age that was deposited adjacent to or upon the eroded edge of the Merced Formation strata.

Merced Formation

The Merced Formation was named by Lawson (1893) for a sequence of predominantly marine Pliocene and Pleistocene strata on the San Francisco Peninsula. He divided the formation into lower and upper subdivisions, with the steeply dipping marine strata in the lower division. The type section of the Merced Formation was selected along the ocean cliff exposures south of San Francisco, from Mussel Rock in San Mateo County northward to Fleishhacker Zoo, north of the San Francisco City and County line.

The base of the type section at Mussel Rock has variously been considered to be a depositional contact (Lawson 1893; Glen 1959; Hall 1965a) or a fault contact (Ashley 1895; Higgins 1961). Based on my own observations, I think that Glen and Hall are correct, and that it is a depositional contact. The lowest strata are clay rich, containing plant fossils, and rapidly change upward into marine deposits. These sediments are similar to that of modern long linear embayments along the San Andreas Fault (Bolinas Bay, Tomales Bay, Bodega Bay) and is an expected depositional sequence for rising sea level transgressing into a long linear valley. The Merced Formation was probably deposited in a long valley within the San Andreas Rift Zone, since it is expected that linear embayments were present in Merced Formation time when the fault was also active. The upper contact of the Merced Formation was placed within a sequence of deformed sandstones by Lawson (1893), while Hall (1965a, 1965b) included all of the deformed strata within the Merced Formation and restricted the overlying unit (Colma Formation) to a thin layer of horizontal beds deposited on truncated Merced strata. The Colma Formation (of Schlocker and others 1958) consists of undeformed, poorly consolidated sandy deposits and is a partial equivalent of the "Terrace Formation" of Lawson (1895).

Stratigraphic sections of the Merced Formation in the Twelvemile Creek area are shown in Figure 3. The stratigraphic sequence extends from the San Andreas Fault on the west to the Serra Fault on the east, with only minor struc-

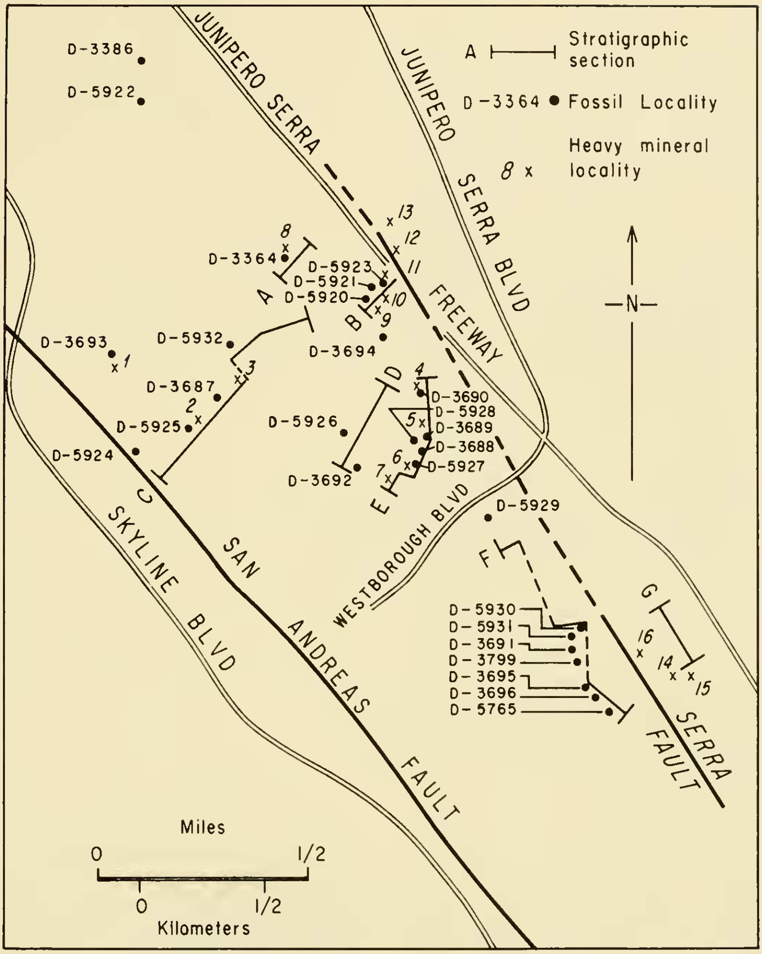


FIGURE 2. Location map of stratigraphic sections, fossil locations, and heavy mineral sample locations in the Twelvemile Creek area.

tural complications. The stratigraphic sequence is about 1000 meters (3000 feet) thick and is incomplete, with fault contacts at both the top and bottom. The lithology of the strata varies from clayey silts or clayey sands to shelly sandstones, with occasional thin peaty layers and thin conglomeratic layers. The sediments are sparsely to richly fossiliferous and are normally poorly sorted.

There is a trend of increasing average grain size of the sediments from the lower to upper part of the stratigraphic sequence. Sediments in the lower part of the sequence are mostly fine grained with some sandy interbeds, while sediments in the upper part of the sequence are mostly sandy with occasional thin conglomeratic interbeds. The conglomeratic interbeds contain polished cherty pebbles and broken shell fragments and represent coarse-grained beach deposits. Also, the upper, coarser sediments contain abundant echinoids, indicating deposition in high-energy conditions typical of beach environments. This interpretation is further supported by the occurrence of many echinoid tests with the apical areas broken away, similar to the breakage of modern echinoid tests produced by waves on beaches, as can be seen on the nearby modern beaches of the San Francisco Peninsula.

The Merced Formation in the Twelvemile Creek area contains both restricted and open marine biotas, characterized by the following species:

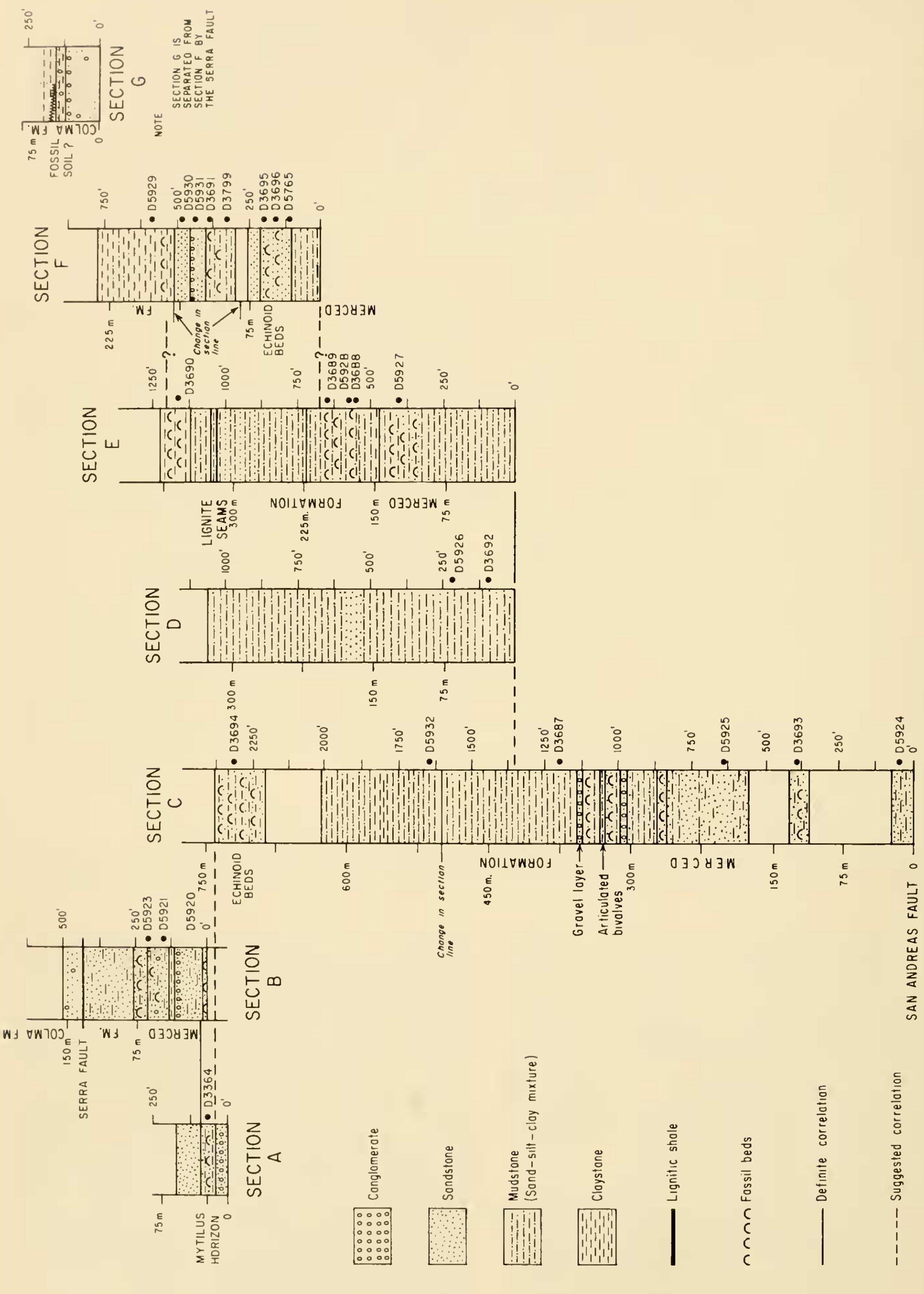


FIGURE 3. Stratigraphic sections of the Merced and Colma formations in the Twelvemile Creek area.

Bivalves
Mytilus condoni Dall, 1890
Clinocardium meekianum (Gabb, 1866)
Solen sicarius Gould, 1850
Tresus nuttallii (Conrad, 1837)
Macoma nasuta (Conrad, 1837)
Gastropods
Crepidula princeps Conrad, 1856
Olivella biplicata (Sowerby, 1825)
Polinices lewisii (Gould, 1847)
Nucella lamellosa (Gmelin, 1790)
Mitrella gouldii (Carpenter, 1857)
Ophiodermella mercedensis (Martin, 1914)
Crustaceans
Cancer sp.
Echinoids
Scutellaster interlineatus (Stimpson, 1856)

With the exception of *Scutellaster*, all species are living today or have closely related species living in the San Francisco area. The genus *Scutellaster* is extinct, but its ecologic niche appears to be presently filled by the genus *Dendraster*, as determined by a comparison of the modern occurrence of *Dendraster* and the inferred paleoenvironment of *Scutellaster* in the Merced Formation.

Age.—An upper Pliocene age for this unit is established by the occurrence of *Scutellaster interlineatus* (Simpson, 1856), *Nassarius moranianus* (Martin, 1914), and *Mytilus condoni* Dall, 1890. The available evidence suggests that the genus *Scutellaster* became extinct by the end of the Pliocene (J. W. Durham, personal communication, 1969) and is therefore an indicator for the Pliocene epoch. *Nassarius moranianus* is restricted to the upper Pliocene and lowermost Pleistocene (Addicott 1965). *Mytilus condoni* is restricted to the upper Pliocene and lower Pleistocene (Addicott 1974). Mandra (1949) reported it (as *M. highoohiae* Mandra, 1949) as a lower or middle Pliocene species, but its occurrence in the same horizon as *Scutellaster interlineatus* places it in the upper Pliocene (as used in central California). *Nassarius moranianus* has been found throughout the stratigraphic sequence, but *Mytilus condoni* and *Scutellaster interlineatus* have been found only in the upper part of the sequence. A bioseries of *Ophiodermella* is present in the Merced Formation, of which *Ophiodermella mercedensis* (Martin, 1914) is restricted to the Twelvemile Creek sequence and its correlatives, and is apparently restricted to the upper Pliocene.

Correlation.—The Merced Formation strata in the Twelvemile Creek area correlate with the upper marine part of the Merced Formation in the ocean cliff section a few miles to the northwest (Figure 4). This is the second unit in Hall's (1965a, 1965b) fourfold subdivision of the type section of the Merced Formation, which includes strata lying between the San Andreas Fault and the marine-nonmarine transition in the formation. In both sections *Scutellaster interlineatus* occurs near the top of the unit, and there is a trend of increasing grain size toward the top of the unit where coarse-grained beach deposits occur. Also, the same locally derived, heavy-mineral suite is present in the sands in both areas. The Twelvemile Creek section is about 1000 meters (3000 feet) thick and is incomplete, compared to the same unit in the ocean cliff section which is about 1400 meters (4200 feet) thick and also incomplete. This is the thickest unit in the Merced Formation, and its outcrop can be traced continuously to the southeast from the ocean cliff section for about 13 kilometers (8 miles) to the southern city limits of San Bruno and may extend discontinuously for several kilometers beyond that point.

In the ocean cliff section the transition from older marine sediments to younger nonmarine sediments is marked by a change in heavy mineralogy of the sands from a locally derived suite of sediments (basically from the Franciscan Formation metasediments) to a distantly derived suite of sediments from the Sacramento-San Joaquin Valley (Hall 1965a). The Franciscan Formation-derived heavy mineralogy has a moderate proportion of hornblende and a very low proportion of hypersthene (Hall 1965a), diagnostic Franciscan minerals such as jadeite, pumpellyite, lawsonite, and glaucophane in quantities up to 10–20 percent of the sample (Yancey and Lee 1972), and commonly has picotite and enstatite, also characteristic of Franciscan terrains. The Sacramento-San Joaquin-derived heavy mineralogy has a lower proportion of hornblende and higher proportion of augite and hypersthene than the Franciscan-derived mineralogy. The proportion of augite plus hypersthene may reach 50 percent of the sample, with augite normally more abundant than hypersthene. Hall (1965a) demonstrated the source of the pyroxenes to be the late Cenozoic volcanics of the Central Valley and concluded that the sands of the nonmarine part of the

TABLE 1. CHECKLIST OF MERCED FORMATION FOSSILS IN THE TWELVEMILE CREEK AREA.

	D-3364	D-3386	D-3687	D-3688	D-3689	D-3690	D-3691	D-3692	D-3693	D-3694	D-3695	D-3696	D-3799	D-5765	D-5920	D-5921	D-5922	D-5923	D-5924	D-5925	D-5926	D-5927	D-5928	D-5929	D-5930	D-5931	D-5932
BIVALVIA																											
Yoldia limatula		1																									
Acila castrensis		1																									
Mytilus condoni	50			3											6							4					
Mytilus coalingensis							1							1													
Mytilus sp		10																								2	
Modiolus sp																							1				
Adula californica						1	1		2		5			1													
Clinocardium meekianum				1		4			12		4	4							20								
Clinocardium sp															5						3	1					
Spisula albaria coosensis	2										12	60															
Spisula mercedensis				1																							
Spisula mossbeachensis									10		7	3															
Tresus nuttallii				3	3						2	4		8						2							
Tresus sp									1									1					1				
Solen sicarius				3		1		4													1						
Siliqua patula						1		1	1			3								1	3						
Macoma nasuta		3	2	4		4		3			1					4	4			4	4						
Macoma sp								1			2	2			1												
Macoma inquinata																			30								
Protothaca tenerrima														3													
Saxidomus sp																						1					
Transennella tantilla		10				1								1													
Compsomyax subdiaphana	2											2															
Cryptomya californica		6	5	30				2													2		2				
GASTROPODA																											
Bittium sp	2														50												
Epitonium tinctum																							1				
Epitonium sp									3																		
Calyptraea filosa	7																										
Crepidula aff. C princeps	50														15												
Polinices lewisii			1	1	2	2			4			3						2			4						
Nucella lamellosa		2		5	2	1			15	4	13	3	3											7	3		1
Nucella canaliculata		2							1	3	1	1		1													
Nucella emarginata										1														1			
Neptunea tabulata	1		1	3	3	3	2	2	4	1	1	1															
Amphissa reticulata						1																				1	
Mitrella gouldii	20	12				3			22			2			4		3				7						
Searlesia sp?		1																									
Cancellaria sp?																											
Nassarius moranianus		2		12		4			3					7			8	2			3			3			
Nassarius sp	1														1							1			1		
Nassarius mendicus		10							1																		
Olivella biplicata		1		1		4			13				2	2				1			1						
Ophiodermella mercedensis		3		6		10			12				7	20	4		2	2			2			4			
Ophiodermella graciosana									1																		
Ophiodermella sp	5											2													6		
Turbonilla sp	6																										
ARTHROPODA																											
Cancer sp	2	1									1																
Callianassa sp																									3		
Balanus sp	8			2		1			5		5		1											2			
ECHINOIDA																											
Scutellaster interlineatus							2			25	100	10														3	
Scutellaster sp									5																		
BRYOZOA		1																									

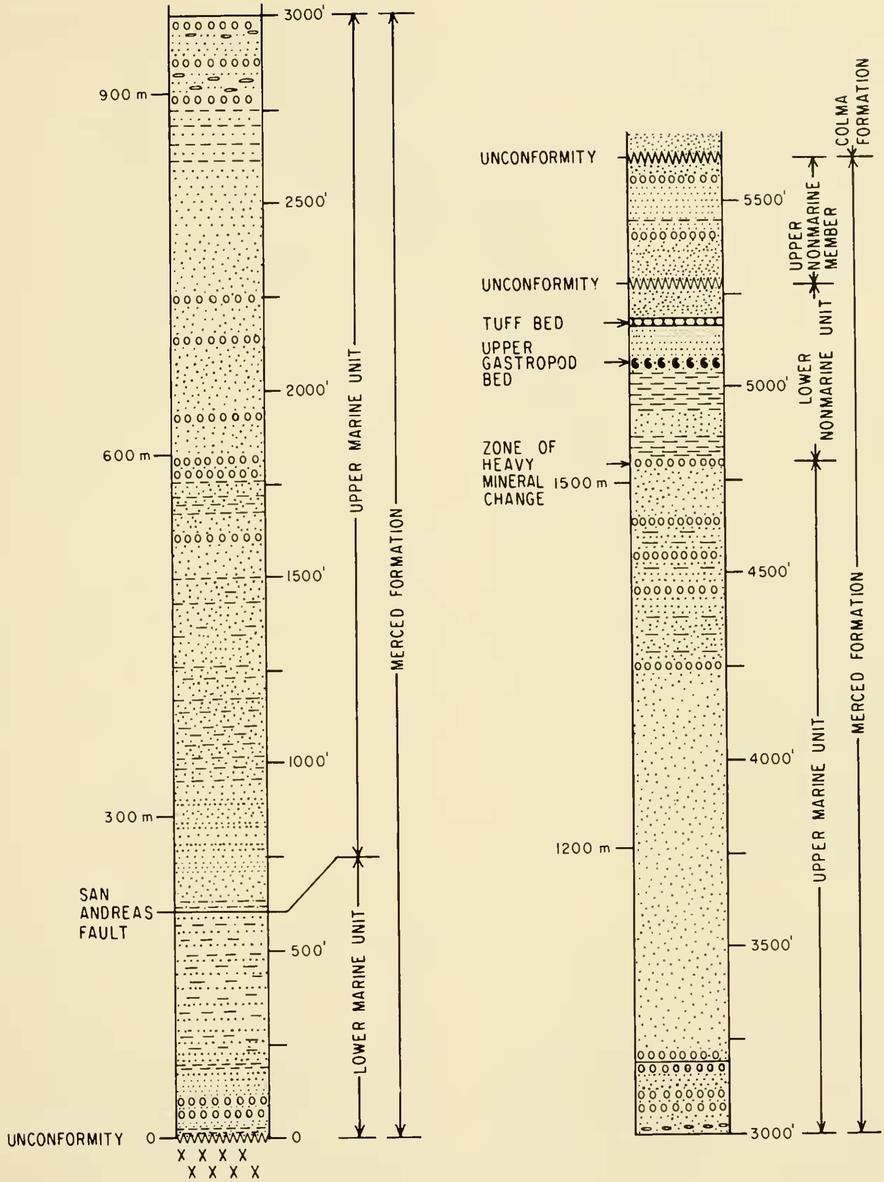


FIGURE 4. Columnar section of the Merced Formation strata from the type section of the formation (compiled from Glen 1959, and Hall 1965a, 1965b).

Merced Formation were derived from Sacramento-San Joaquin drainage that had newly established an outlet through the San Francisco Bay area.

In the Twelvemile Creek area the heavy mineralogy of the Merced Formation is the same throughout the section (samples 1–11 in Table 2) and is similar to the mineralogy of the marine part of the Merced Formation in the ocean cliff section. It contains a basically Franciscan-derived heavy mineral suite with conspicuous glaucophane in the samples. A few of the samples in this suite contain small but significant amounts of sphene and apatite, occasionally accompanied by high hornblende content: minerals indicative of granitic sources (Yancey and

TABLE 2. HEAVY MINERALOGY OF SANDS FROM THE MERCED (COLUMNS 1–11) AND COLMA (COLUMNS 12–16) FORMATIONS IN THE TWELVEMILE CREEK AREA. Percentages are based on nonmicaceous-nonopaque minerals, and are based on minerals of approximately the same hydraulic character. Other minerals are tabulated separately.

Samples	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Nonmicaceous, nonopaque minerals																
Hornblende	19	12	24	40	55	23	37	19	43	25	39	39	42	47	37	46
Oxyhornblende					1	2		2			1	3			3	
Glaucophane	4	7	5	6	2	5	8	7	3	3	15	9	15	10	9	3
Tremolite-Actinolite	1	3	3		1		3	5	1	2	9	4	9	9	6	9
Hypersthene	1	5	2	3	1	2	1	4	4	9	3	1	6	1	1	
Augite	8	8	9	9	4	12	12	14	13	10	12	16	12	11	16	18
Jadeite	10	11	25	18	14	6	15	8	3	5	5	10	2	6	5	2
Enstatite	2		1	1	2			4			2		2	1	2	1
Epidote	10	8	5	3	4	7	6	10		15	4	6	1	4	5	3
Zoisite		1	1					1								
Pumpellyite	1	2	1			1			1							
Lawsonite			3	1		4		2	1				2			1
Garnet	7	8	2	3	1	10	3	6	2	1	2	2	1	1	2	4
Apatite	2	1	4	3		2	2	1	3							
Tourmaline	3								1						1	1
Zircon	8	6	6	4		10	1	5	9	7	1	2	4	2	2	4
Sphene	4	5	5	6	12	4	9	7	8	3	2	2	2	2	3	3
Rutile	1					1		1	1	1	1					
Picotite	19	23	4	3	3	11	3	4	7	19	4	6	2	6	8	5
%	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Opaque minerals																
Magnetite-Ilmenite	52	36	9	13	18	40	14	20	15	45	4	23	23	20	27	23
Hematite-Goethite	9	7	3	6	4	7	4	11		2	1	19	9		7	1
Leucoxene	11	9	7	2	4	1	1	9	2	6	4		8		1	2
Pyrite	1				1											
Micaceous minerals																
Biotite		2	1	2	3	3			11		1	188	51		9	1
Chlorite	2															
Others																
Unknowns	5	6	6	4	2	6	3	6	4	3		2	4	1	1	1
Carbonate					3	1										
Alterites	196	395	90	109	70	170	88	273	165	173	192	439	330	84	330	280

Lee 1972). Granitic rock outcrops west of the San Andreas Fault were probably the source of these minerals.

Colma Formation

Unconformably overlying the Merced Formation strata is a widespread unit of flat-lying undeformed deposits that were deposited on irregular topography. These deposits were defined and named by Schlocker and others (1958) as the Colma Formation, with a type area near the town of Colma, about 3 kilometers (2 miles) east of the ocean cliff section of the Merced Formation. In its type area (where no significant section is presently exposed), the Colma Formation is separated from the Merced Formation strata by the Serra Fault. The formation is probably a few hundred meters thick in this area, although the thickest sequence reported by Bonilla (1959) was 75 feet (23 meters), and the thickest sequence measured in this study is about 60 meters (200 feet).

The Colma Formation is partly an equivalent of the "Terrace Formation" of Lawson (1893). Lawson gave this name to strata overlying his Merced Formation because he believed them to be terrace deposits derived from the underlying Merced. Schlocker and others (1958) renamed and redefined the strata of this interval because deposits from at least two tectonic episodes are included in it. Most of the "Terrace" deposits along the ocean cliffs are most properly placed in the Merced Formation as redefined by Hall (1965a, 1965b).

The Colma Formation consists mostly of unlithified sand of brown to yellowish color, and this is commonly the only lithology present in outcrops. A few pebble horizons can be found in most large outcrops, but they do not characterize any particular part of the section. In one zone near the road level of the Junipero Serra Freeway in South San Francisco (near heavy mineral locality 12), cobbles of a whitish, cherty rock are found in the sands. Scattered fossil fragments are found in the Colma Formation, but these could be reworked from Merced Formation strata, and no complete shelly fossils have been found. Bonilla (1959) more fully describes the lithologies of this part of the Colma Formation.

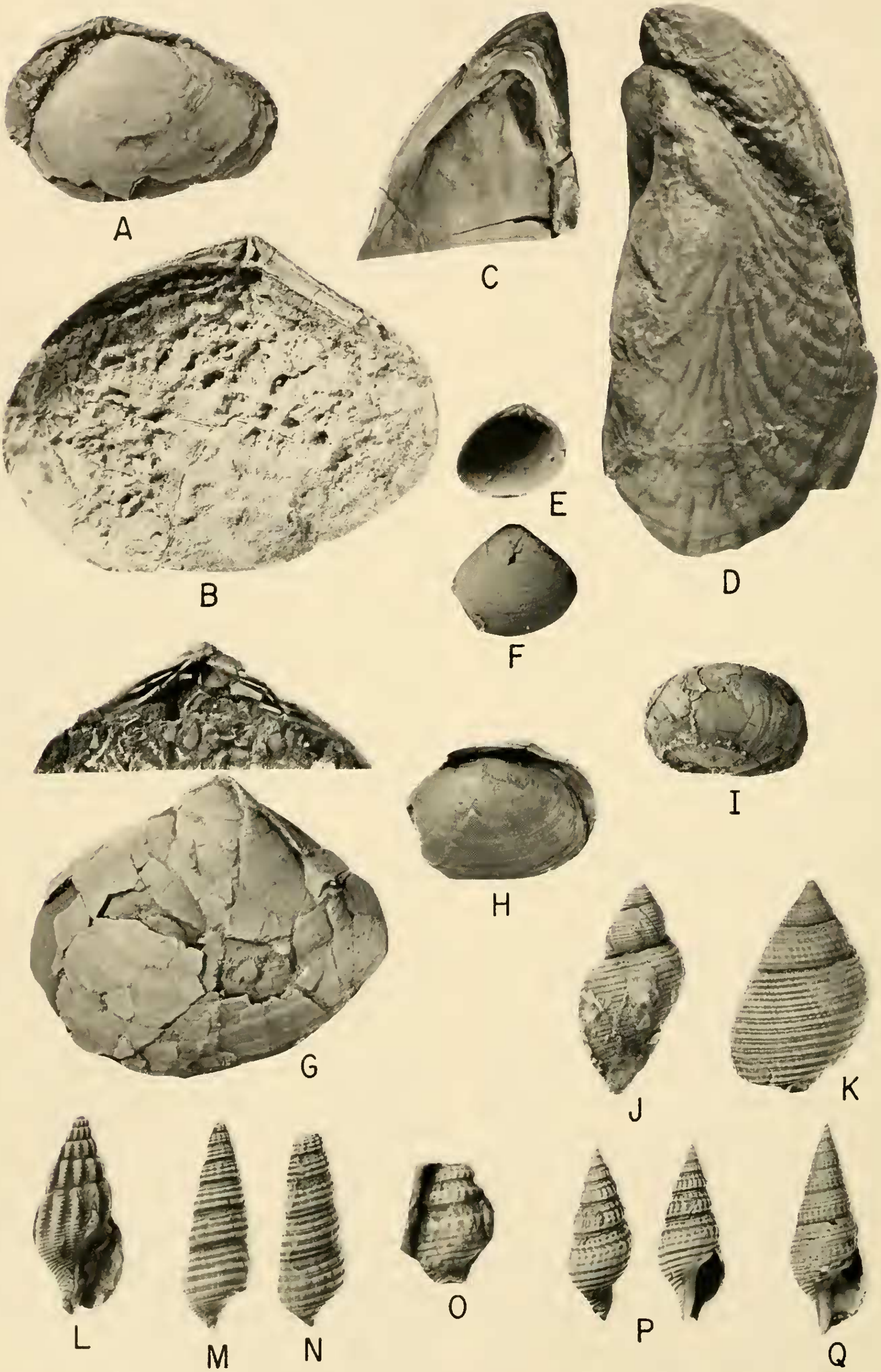
Upper Part.—An upper part of the Colma Formation is here distinguished for a group of strata that are lithologically distinct from the typical Colma but appear to be more or less conformable with the typical Colma. This set of strata is probably equivalent to what Bonilla (1959) called the "Older Alluvium" in areas a few kilometers to the north, and to deposits of clayey sand in the Twin Peaks area of the San Francisco North quadrangle mapped as alluvium by Schlocker (1974). This unit is characterized by sediments that are usually very poorly sorted and have a high clay content. The most common lithologies are poorly sorted, clayey, silty sands and sandy silts or clays containing abundant plant fragments. Bonilla (1959) noted that these strata are often more resistant to erosion than the underlying sediments and that they produce steep erosion slopes. These sediments are distributed topographically above the friable sands of the lower Colma Formation.

The clay-rich character of these sediments, their high organic (plant) content, and their very poor sorting indicate that they may be fossil soil horizons. Within the clay-rich horizons there is evidence of local channeling and reworking of deposits. Near heavy mineral locality 15 a very local unconformity with about 20 feet of relief was noted, and the overlying deposits contain horizons with clasts of unconsolidated clayey sand which are derived from immediately underlying deposits. This unit is probably the source of fossil tree trunks found about one kilometer south of Colma (Martin 1916).

Age.—Fossils of the Colma Formation (fossil woods) are not useful for age determination, but the entire formation can be dated as post-lower Pleistocene by stratigraphic position, since it overlies Merced Formation strata which have been interpreted to be as young as the Pleistocene Irvingtonian stage (Hall 1965a, 1965b). The main part of the Colma Formation was probably deposited during a higher stand of sea level, while the finer, clay-rich deposits probably accumulated during a lower stand of sea level during the late Pleistocene.

The sandy portion of the Colma Formation appears to be mostly reworked dune sands, judging from the rather uniform fine to medium grain size, moderate sorting, and lack of fossils or sedimentary structures apart from horizontal or subhorizontal bedding. Schlocker (1974:71) also noted that the Colma Formation deposits have about the same median grain size as dune sands. Assuming that the ocean beach was the main source for dune sands, deposition of the Colma Formation sands during a Pleistocene high stand of sea level is most probable since the source would be close to the area of deposition. Similarly, deposition of the upper fine-grained clay-rich deposits is most likely during a low stand of sea level when little wind-blown sand would be carried to the San Francisco Peninsula from the distant ocean beach, which would be about 50 kilometers to the west at that time.

Heavy Mineralogy of the Sands.—Colma Formation sands (samples 12–16 in Table 2) studied for comparison with the Merced Formation show that the Colma Formation in the Twelvemile Creek area has a composite heavy mineralogy and that the minerals are extensively altered, probably by weathering before and after deposition. The sediments are not purely Franciscan-granitic in origin nor purely Central Valley in origin, and are probably a mixture of both types. Colma Formation sands in the San Francisco North quadrangle (Schlocker 1974:pl. 2) have a heavy mineralogy similar to that of the upper portion of the type Merced Formation (Hall 1965a), which is derived mostly from a Central Valley source area. These differences in heavy mineralogy in different areas apparently show local influences on sedimentation, but the majority of Colma Formation sands are probably derived from Central Valley sources.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Age Diagnostic Fossils of the Merced Formation

Several groups of fossils are potentially important for correlations of Merced Formation strata, especially the mytilids, myids, mactrids, nassariids, turrids, and echinoids, all of which have many species in the upper Cenozoic and have been reasonably well studied. The echinoids and the turrids appear to be the most useful groups, having species with short stratigraphic ranges and occurring commonly in the Merced Formation.

Species of the echinoid genus *Scutellaster* are common in coarse-grained marine strata and have restricted stratigraphic ranges. Glen (1959) records the stratigraphic ranges of *Scutellaster oregonensis* (Clark) and *S. interlineatus* (Stimpson) in the ocean cliff section of the Merced, and points out the close relationship of the two species. It is probable that *S. interlineatus* evolved from *S. oregonensis* and that they have mutually exclusive biozones, which allows precise correlation of Pliocene strata containing these species.

Species of the turrid genus *Ophiodermella* also have restricted stratigraphic ranges in the Merced Formation and may be part of an evolutionary lineage including the species *O. graciosana* (Arnold, 1907), *O. mercedensis* (Martin, 1914), and *O. incisa* (Carpenter, 1864). The stratigraphically lowest-ocurring species is *O. graciosana* of which only a single individual was found close to the base of the section (loc. UCMP D-3693) in the Twelvemile Creek area and was not seen in the available collections from the ocean cliff section. The species has also been found in exposures of the Merced? Formation in northern Santa Clara County (Addicott 1969) that correlate with the oldest part of the Merced Formation in the ocean cliff section.

The species *O. mercedensis* occurs commonly throughout the Twelvemile Creek section, occurring with *O. graciosana* only near the base of the section, and occurring alone in the upper part of the section. In the ocean cliff section it also occurs commonly throughout the section, and all of the *O. graciosana* var. *mercedensis* reported by Glen (1959) appear to be typical *mercedensis*. *O. mercedensis* is here considered a valid species and not a synonym of *O. graciosana*, based on its weaker ribbing and tendency to be higher spired than *O. graciosana*. It does not show much variation in sculpture within the Merced Formation, with the intensity of spiral ribbing and radial ribbing being quite uniform. The height of spire is slightly variable, and a few individuals show a noticeable weak keel in the position of the sinus. Glen's (1959:178) statement that *mercedensis* varies greatly in spire height and ornamentation is based on examination of badly weathered specimens, and these variations are not representative of the Merced Formation *Ophiodermella*.

The living species *O. incisa* appears in the stratigraphically higher Upper Gastropod Bed of the Merced Formation. These three species are biostratigraphically restricted in the Merced Formation, and perhaps can be used for local and regional correlations.

O. graciosana can be distinguished from *O. mercedensis* by its stronger and less numerous spiral ribs, presence of a weak keel, and radial

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Figure 5. Characteristic and distinctive fossils of the Merced Formation in the Twelvemile Creek area. A. *Macoma inquinata* (Deshayes) (0.7) USNM 251798, loc. UCMP D-5924. External view of specimen with mismatched valves showing dentition and rounded posterior margin. B. *Macoma nasuta* (Conrad) (0.6) USNM 251799, loc. UCMP D-3688. C. *Mytilus condoni* Dall (0.7) USNM 251800, loc. UCMP D-3364. View of hinge of a large valve. D. *Mytilus condoni* Dall (0.6) UCMP 10928, loc. UCMP D-5927. Specimen with paired valves showing strong divaricating sculpture, but partly distorted due to sediment compaction. E. *Transennella tantilla* (Gould) (5) USNM 251801, loc. UCMP D-3386. F. *Transennella tantilla* (Gould) (3.2) USNM 251802, loc. UCMP D-3386. Slightly oblique view of average size specimen. G. *Spisula albaria coosensis* Howe (0.6) USNM 251803, loc. USGS Cenozoic M-5754. Internal and external views of a valve showing hinge and growth lines. H. *Cryptomya californica* (Conrad) (0.7) USNM 251804, loc. UCMP D-3688. I. *Crepidula* aff. *C. princeps* Conrad (0.7) USNM 251805, loc. UCMP D-3364. Oblique apical view of a typical specimen. J. *Nucella canaliculata* (Duclos) (0.7) USNM 251806, loc. UCMP D-5765. Side view of a very elongate specimen. K. *Nassarius moranianus* (Martin) (0.7) USNM 251807, loc. UCMP D-3688. L. *Amphissa reticulata* Dall (1.4) USNM 251808, loc. UCMP D-3690. M. *Bittium* sp. (1.4) USNM 251809, loc. UCMP D-5920. N. *Bittium* sp. (1.4) USNM 251810, loc. UCMP D-5920. Side view showing sculpture with secondary spiral ribs on body whorl. O. *Ophiodermella graciosana* (Arnold) (1.4) USNM 251811, loc. UCMP D-3693. Side view of fragmentary specimen showing sculpture of strong nodes on whorls. P. *Ophiodermella mercedensis* (Martin) (1.4) USNM 251812, loc. UCMP D-3364. Apertural and abapertural views of a typical specimen. Q. *Ophiodermella incisa* (Carpenter) (1.4) USNM 251813, loc. UCMP B-4811 (from the Upper Gastropod Bed, at Thorton Beach State Park).

ribs across the upper half of the whorl, and *O. incisa* can be readily distinguished from *O. mercedensis* by its higher spire and fine spiral ribs, and lack of radial ribs except on the tip of the spire. These species show trends of increasing spire height, increase in spiral ribs, decrease in strength of radial ribs, and decrease in inflation of whorls through geologic time.

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